Capstone Design Project Experience: Lunar Ice Extraction Design

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CAPSTONE DESIGN PROJECT EXPERIENCE: LUNAR ICE EXTRACTION DESIGN

Abstract

A group of senior undergraduate students came together as part of a non-traditional capstone design project. The assignment was to take part in the NASA RASC-AL competition and required adjustment to the class curriculum. Two examples are that a direct point of contact from the customer would not be possible as there is no specific person at NASA meant to act as the customer and the submission deadline was after the semester concluded. The students were all from the mechanical engineering department and had a fascination with space technology but came from vastly different demographic backgrounds representing multiple spheres of diversity. This diversity brought unique and unexpected approaches to the project. The project required close interaction of the group throughout and after the semester to accomplish a very difficult goal: the design of a full scale lunar ice extraction facility capable of running autonomously and producing at least 100 metric tonnes of ice per year. The operational plan is to be accompanied by a detailed budget and launch plans to begin taking effect in 2025. Having no experience working with one another prior to this project, the group was required to quickly develop a productive team ethos to address such a large challenge. The aim of this study is to assess the outcomes and reactions during a project from a diverse group of students attempting to complete an unusual capstone design. Accompanying this are pre-, intra-, and post-project surveys to assess effectiveness of the group on key project issues. The primary research questions to answer are: does the perception of the group regarding effectiveness positively correlate with the feelings of ownership of the project and feelings that the individual students' passions are being considered. Further, because the competition is staged and set to go on the full academic year, the students are interviewed regarding plans on continuing the project beyond the current semester when the majority of the team will have graduated.

Introduction

The goal of this project is to create a concept design for an automated lunar ice mining facility. The facility will harvest ice from the moon. There is an estimated 3-trillion tons of water ice present at the poles of the moon [1]. Knowing this, the water can be extracted and separated into its constituent parts for use as a LOX-Hydrogen rocket fuel for deep space missions.

Design

The design consists of several main components and can be seen in the figure below. An overview of the facility design follows. A nuclear reactor provides electrical power and waste heat to the facility. The electrical power is used to drive several components of the system. The waste heat is used in the heat pipes, which are embedded in the lunar regolith. These heat pipes will transfer the waste heat into the regolith. The ice in the regolith is vaporized, captured within a membrane and piped to a compressor. In the compressor the water vapor is compressed, condensed, and then stored until needed. When fuel is needed the water is moved into an electrolysis unit and disassociated into hydrogen and oxygen. The hydrogen and oxygen are then compressed, liquefied, and stored in separate vessels from which they can be dispensed.

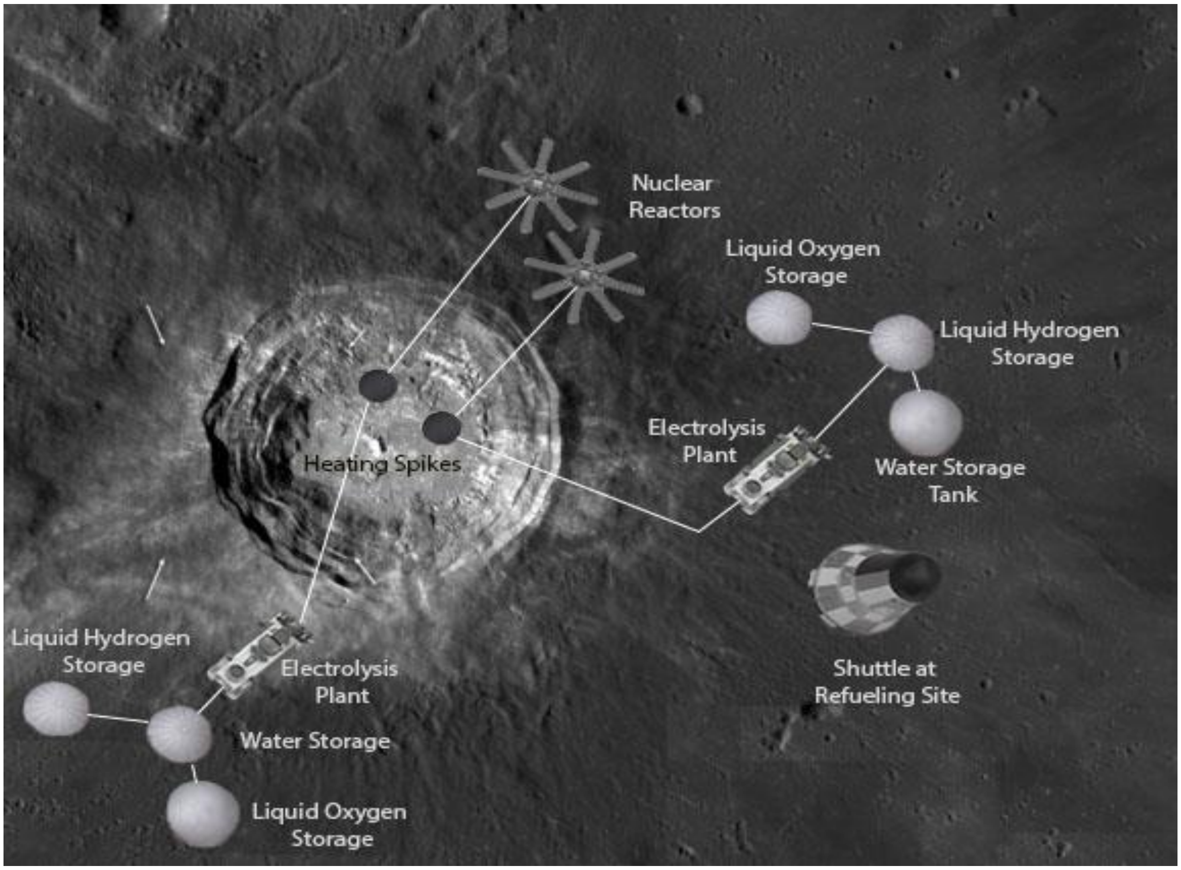


FIGURE 1: OVERALL OPERATION

Power Supply

There are several methods of supplying power to a lunar surface mission. Several are in use for current NASA missions. What follows is a discussion of those methods and how they could be used for the ISRU water mining mission.

The primary challenge for solar power of any kind is the amount of power that can be generated. The inherent loss of efficiency incurred by the conversion path from a photon to DC current on the ground. During the groups preliminary estimates of power requirements for heating the water from ice to vapor, solar power does not produce the necessary power with a reasonable number of solar panels. During 'back of the napkin' calculations, the team determined it would take several football fields worth of panels to simply provide the heat energy needed (assuming no efficiency loss). Therefore, the prospect of using solar power was scrapped from the design.

SUSEE (Space Nuclear Steam Electric Energy)

The use of a nuclear reactor for the design arose from the need of large amounts of heat for heating the lunar regolith. The SUSEE system provides 10MW(electric) and approximately 50 MW(thermal) of waste heat that is used to heat the lunar regolith and vaporize the ice.

Insulation and Internal Heating

A Radioisotope Heater Unit (RHU) contains a Pu-238 fuel pellet about the size of a pencil eraser and outputs about 1 Watt of heat. (The entire RHU is about the size of a C-cell battery.) These should work really well in combination with insulation. The following materials are commonly used by NASA:

1. Aerogel: 99.8% air and the rest is silica/glass.
2. Gold paint: Commonly used on rovers, gold paint's high reflectivity helps reduce energy that is radiated from body.

Dissociation of Water: Electrolysis

This method is currently used in industrial applications. It involves using electricity to disassociate [2]the water into hydrogen and oxygen which is then stored. This method is well understood in industry and required little research. This offered the project a way forward without requiring deep research into the disassociation.

Water Vapor Capture

Capturing the water vapor is the crux of this project. The water on the moon exists as ice below the surface. There are two main methods of extracting the water. The first is to excavate the surface and separate the water from the regolith. This method involves moving over 660 tonnes of lunar regolith to retrieve 100 tonnes of water. The temperatures of the lunar crater range from 30 to 40 K. This creates difficulties when operating any machinery with moving parts.

The second method of extracting ice from the regolith is heating the ice/regolith to approximately 220 K, which is the temperature required to vaporize water in a near vacuum. Using this method allows the water to vaporize. This will take place in a vacuum and there will be a pressure differential in all directions. However the vapor will eventually move to the surface as the path of least resistance. This vapor will then be captured. A membrane will be placed on the surface to capture the water vapor. Edges of the membrane are remote from the source of heat and affixed to the regolith so as to create a seal. This membrane will feed a hose that will then transport the vapor to be condensed and compressed.

Project Impact Statement

The facility provides fuel for future space missions available outside of the earth's gravity. Since the pull of gravity is so great from the Earth in comparison to the Moon, there is a significant energy savings by using fuel from the surface of the Moon. For example, a mission to Mars could be reduced by roughly 68% yielding a savings of around $5.8 billion per mission [3]. Missions to deeper space destinations, such as Europa, could see even more savings. This facility will save a significant amount of money for NASA missions that can be used for further exploration and technological development.

Launching a nuclear reactor to the moon has potential environmental and political impacts. The main concern is a failed launch with nuclear material on board. This can be overcome by storing all nuclear materials in a lead case that will not break open, similar to the casks used to transport nuclear material around the country. There is no way to completely remove this threat. However, with the proper safety precautions, this risk is minimal. Having a nuclear reactor on the moon may also has political implications. However, these political issues go beyond the scope of this paper and are not considered.

Beyond economic, environmental, and political impacts, there are significant technological impacts that should be considered. With an estimated 3-trillion tons of water on the moon [1], only harvesting 100-tonnes per year yields more resources than can be realistically used. However, with potential use of the water for other missions, this technology – once proven – may become vital to the survival of a moon-based colony or may be used as a source for water for deep space missions. Another technological impact is the use of large scale In-Situ Resource Utilization (ISRU) technology. Thought to be vital to deep space travel, ISRU research is currently only theoretical and has never been implemented to any significant scale. If this mission is successful, mining of resources for use both in space and on earth could become the way of the future. By enabling humans to "live off the land," there are really no limits to where we can go in the solar system.

Student Outcomes

In order to evaluate the student outcomes this project had, anonymous surveys were conducted to shed light upon various aspects of the experience. A survey consisting of 10-questions was created by the student project leader to address all students involved. Oversight of this was confirmed by an outside student group and the faculty advisor for feedback. Participants were asked questions relating to what they gained from the experience and overall impressions/conclusions. All questions asked had multiple-choice answers. Questions were chosen based on prior research experience of the group members and were tailored to expose the most important outcomes of a large project such as the one undertaken by the group.

Conclusions

Transient Heat Transfer Calculations

Several calculations were performed to ascertain how much water, in the form of ice and vapor, could be extracted from the lunar regolith. Approximately the top 40 cm of the lunar regolith is desiccated [1] thus creating a need to heat deeper into the regolith than first expected. Many of the first calculations assumed a desiccation depth of only 10 cm.

The first set of transient heat transfer calculations were performed assuming a constant surface heat flux [4]. The heat flux ranged from 117 W/m^2 to 1,350,000 W/m^2. The formula was put into Microsoft Excel so a Goal Seek could be performed to find the time, t, it would take to heat 1 meter below the surface to 220K. These values are presented in Table 1: Surface Heat Flux Transient Values.

TABLE 1: SURFACE HEAT FLUX TRANSIENT VALUES

Source	Heat Flux (W/m^2)	Time (days)
Radiation	117	95.86
Sun	1350	54.28
Nuclear	2000	50.63
1000 Suns	1350000	23.57

Once the surface heat flux calculations were completed it was found that producing the amount of water would require a massive power source producing a large amount of heat flux. This path was laid aside for a constant temperature transient process which could utilize waste heat from the nuclear reactor. Equation 1: Constant Surface Temperature Transient Heat Transfer [3], below, was put into Excel and a goal seek was again performed to find the time, t, it would take to heat 1 meter below the surface to 220 K. These values are presented in Table 2: Surface Constant Temperature Transient with the surface temperature.

EQUATION 1: CONSTANT SURFACE TEMPERATURE TRANSIENT HEAT TRANSFER [3]

$$\frac{T(x,t) - T_s}{T_i - T_s} = \operatorname{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right)$$

TABLE 2: SURFACE CONSTANT TEMPERATURE TRANSIENT

Temperature (K)	Depth (m)	Time (days)
500	1	735.96
500	2	2943.83
850	1	362.99
850	2	1451.97
1100	1	286.98

The amount of water vapor recovered from the surface heating scenarios was promising assuming a top 10 cm of desiccation in the regolith. Once the proper source was consulted and the correct value of desiccated regolith (top 40 cm) was discovered a new path was needed [1]. This involved using the most promising surface heat transfer method, using a constant temperature device, and placing it within the regolith.

After much discussion a metal stake was designed to utilize waste heat from the nuclear reactor. The stakes have tubes running down the outside. These tubes will “shoot” high pressure oxygen through them and into the regolith as they are being placed. This oxygen will loosen the regolith, making the placement of the heat pipes easier. The stakes are placed by a rover that will be connected to the lander. They will be driven approximately 1.5 meters into the surface. They will also have a block unit on the surface that has the heated coolant from the nuclear reactor flowing to them. The heat from the coolant will then transfer to the stake and then into the regolith.

A transient thermal model was created and run in ANSYS. This model, seen below in Figure 2: Transient Thermal Flow Analysis, shows that the initial volume assumed from the heat pipes was incorrect. The image shows a single heat pipe being heated to a constant temperature of 800K. This initial volume was assumed to be a cylinder with a radius of approximately 1 meter centered on the heat pipe. As can be seen, the ANSYS model shows that the heated volume would be a sphere with a radius of about 1.25 meters. The reason the sphere appears to move more downward is because the simulation did include radiation bleeding off energy from the surface with the correct emissivity of 0.9 for lunar regolith. Once the top portion of the sphere – made up of desiccated regolith – was removed from the volume, it was calculated that each heat pipe would produce 180.47 kilograms of water per year. This leads to each “field” of 255 heat pipes producing 46019 kg of water per year.

Since the mass of water per “field” is not the required 100 tonnes per year, a decision was made to include a second “field” launched shortly after the first. This second system will bring the total water extracted to 92 tonnes per year which is within an acceptable range for this stage of the project.

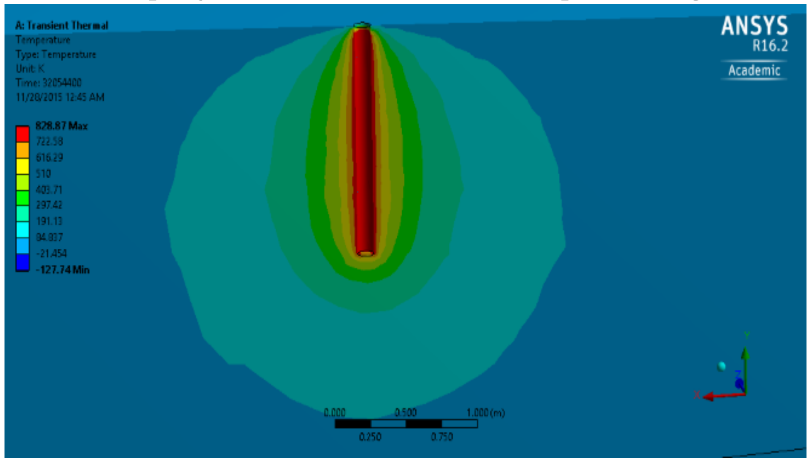


FIGURE 2: TRANSIENT THERMAL FLOW ANALYSIS
MAX TEMP: 800K. MIN TEMP: 40K
SHOWN IS A SIMULATION OF A HEAT SPIKE IN REGOLITH AFTER 1-YEAR OF HEATING. A SPHERICAL VOLUME OF ROUHGLY 2.5-METERS DIAMETER WILL REACH SUBLIMATION TEMPERATURE OF THE WATER ICE.

Tracing reactor coolant through the system

The coolant from the nuclear reactor, at approximately 800 K, represents a useful heat source for the field of stakes. The waste heat from the SUSEE reactor is designed to be radiated into space. Instead this coolant will be piped over the heat pipes to provide a constant temperature heat source for the stakes. The heat will be transferred to the stakes and the coolant will then be pumped back into the reactor.

Technology Readiness Levels

Presented below are the technology readiness levels of the major components of the system.

Component	TRL
SUSEE	3
Electrolysis	4 (since it’s not been used on lunar surface)
Heat Pipes	4
Microwave sintering	5
Valkyries	3
Surface cover	4

Launch Schedule

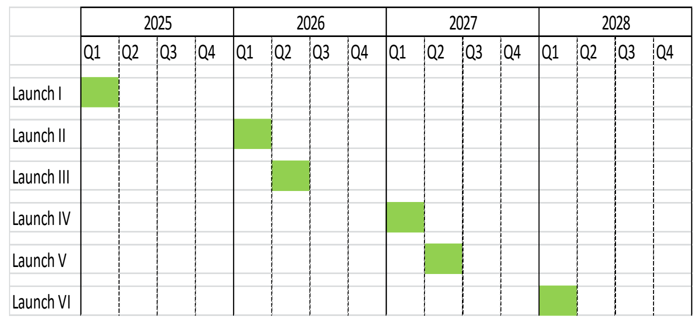
The launch schedule is comprised of six separate launches and be seen in Table 3: Launches and Table 4: Launch Schedule. The first two launches are to find a lunar crater with a large amount of sub-surface ice. These two launches will consist of probes that can be launched into the lunar surface with an orbiting sensor array to analyze the material that is ejected. These analyses allow the following four launches to be positioned in the best crater for the extraction of water.

The next six launches are actually two pairs of launches. Each pair, which can be seen in the tables below, consists of an extraction system which includes the following:

TABLE 3: LAUNCHES

Launch 1/3/5	Launch 2/4/6
Reactor	255 Heat Pipes
3 Valkyries (Robots)	Rover
Water Storage	Surface Membrane
LOx Storage	Umbilicus
LH Storage	Aerogel
Compressors	
RHU	

TABLE 4: LAUNCH SCHEDULE



Budget Analysis

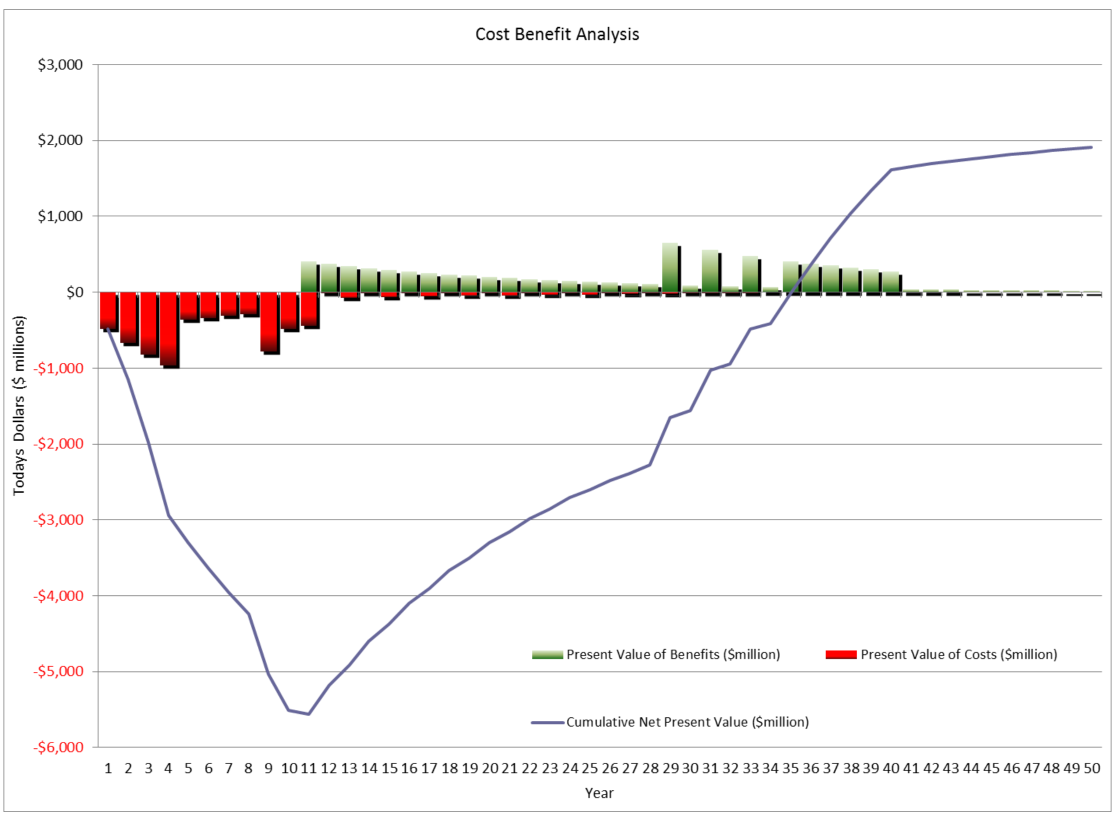


FIGURE 3: COST BENEFIT ANALYSIS

Our budget calculations show a large deficit toward the beginning program with a positive benefit being seen after about 35-years. The initial deficit is due to research and development of the project with no positive impact being generated. However, once operational, which occurs after 10-years, a positive impact is noticeable. Since this is a NASA project, profit is not a primary concern. The main focus is intangible such as the development and implementation of the first large scale off-earth ISRU system. The bill of materials that was used to create this budget can be found in Appendix 1.

Student Outcomes

The survey produced results from all students involved. Questions were designed to yield valuable results from multiple choice options. With the small size of the group, no statistical metrics were used and only trends are considered. Questions were divided into sections and then split randomly throughout the survey to minimize the effects of one question in a particular group on the next. The first section of questions was designed to gather basic information about the students involved. The next section, consisting of only 1-question, was designed to gather a retrospective look on the effectiveness of the project to make students more aware of space technology. The next set was created to gather information on students' feeling regarding perceived ownership, considered interests, and utilization of skills. The final set was created to gather information about how the students felt the project concluded; either with success or failure.

Questions 1, 3, 4, and 10 were designed to gather basic information about the students involved in the project. As can be seen below, question 1 asks summary information about the overall experience. This was ordered in this was as to avoid other questions interfering with the students' perception as the survey went on. As can be seen, the initial question yielded mostly excellent results and nothing below good when asked about the overall experience. When asked how the students heard about the project, all students responded with "From a Professor" (chart not shown).

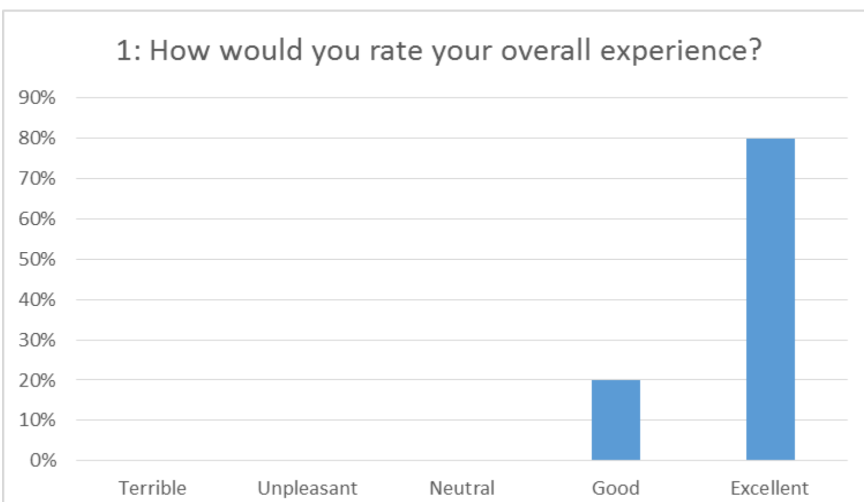


FIGURE 4: HOW STUDENTS WOULD RATE THEIR OVERALL EXPERIENCE.

In considering the difficulty of such a large project, it is common to see a high attrition rate of student members. However, as the semester went on, no students chose to leave the group. Question 4 was posed to find out what caused this. As can be seen below, most students remained involved in the project because of challenge of the topic. However, there were some students motivated to continue by the obligation to the group, or the desire for recognition

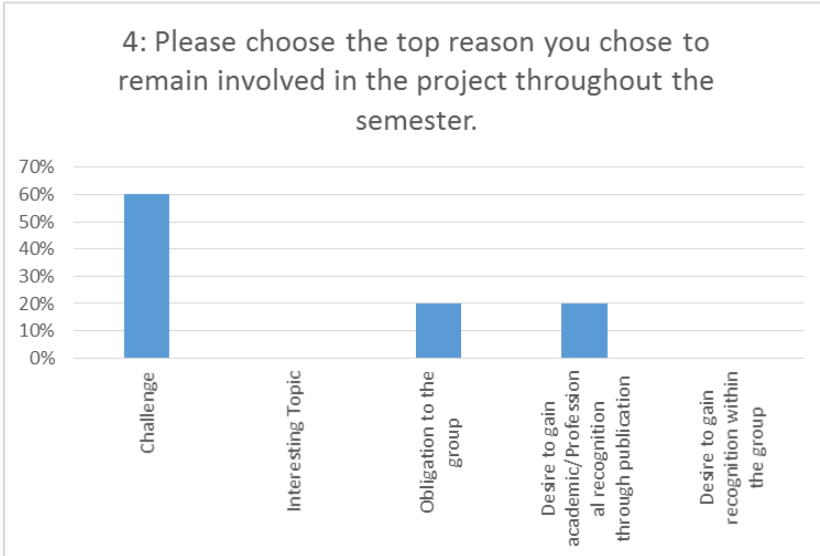


FIGURE 5: WHAT STUDENTS IDENTIFIED AS THE REASON TO REMAIN INVOLVED WITH THE PROJECT

through a potential publication. It was interesting to find that the primary interest was not the topic for any student members. It is clear the students involved were mostly highly competitive.

Question 10 was set up slightly differently to gauge students' attitudes at multiple points during the project. Students' appreciation for scientific research was questioned because it plays such a large role in any design concept project such as the one undertaken. It is important to note from the results that there was a very strong increase in scientific research as the project went on. It

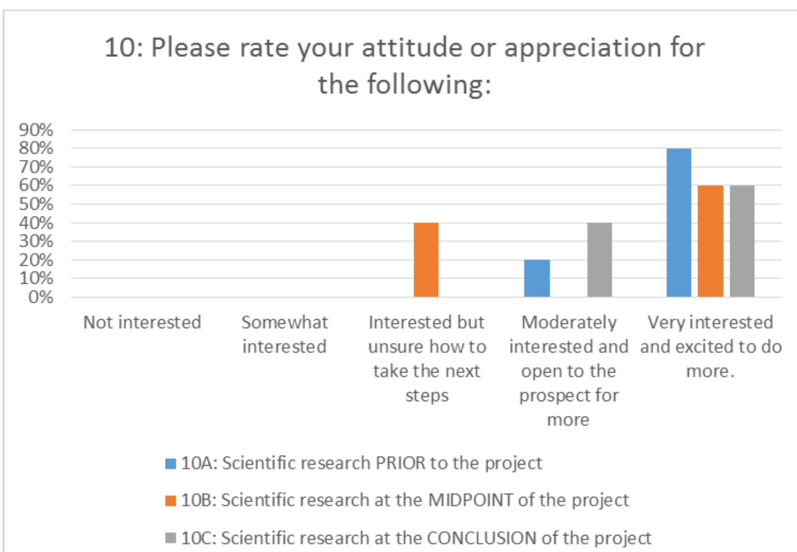


FIGURE 6: STUDENTS ATTITUDE FOR RESEARCH THROUGHOUT THE PROJECT

should be noted that at the midpoint of the project, the group had concluded a multiple month research portion of the project. It is possible the increase in students unsure of how to take the next steps at the midpoint of the project was due to realizing how much was involved with effective research of such a broad topic.

The second question in the survey was designed to gauge students' perceived value of the project as an effect on their knowledge of space technology. As can be seen, the project has had a strong impact on the students involved.

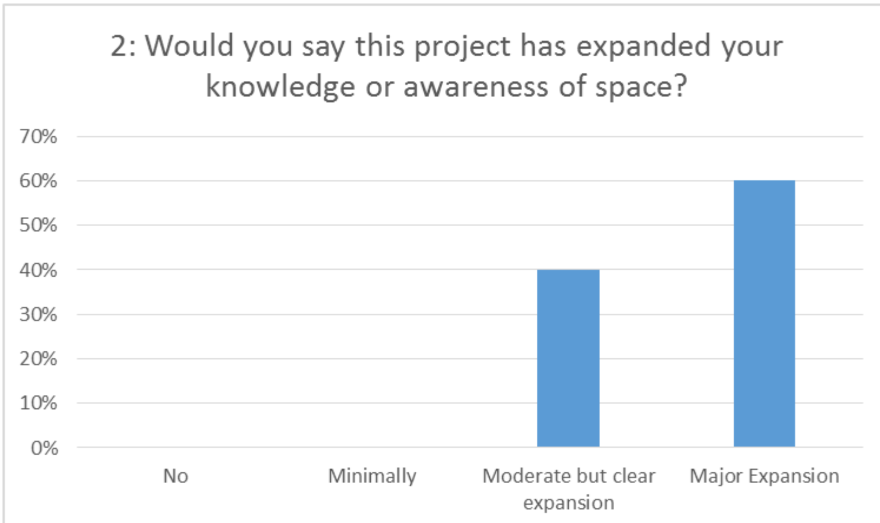


FIGURE 7: STUDENTS PERCEPTION OF HOW THE PROJECT AFFECTED THEIR KNOWLEDGE OR AWARENESS OF SPACE

The next section of questions was designed to gather information about the students' feelings of ownership, interests/passions, and skills and how these were affected by the project. As a means of engaging all students, many discussions were held by the group to incorporate all students' interests into the project. For example, a student with a particular interest in robotics was assigned research into expected mobility issues robots would experience on the lunar surface.

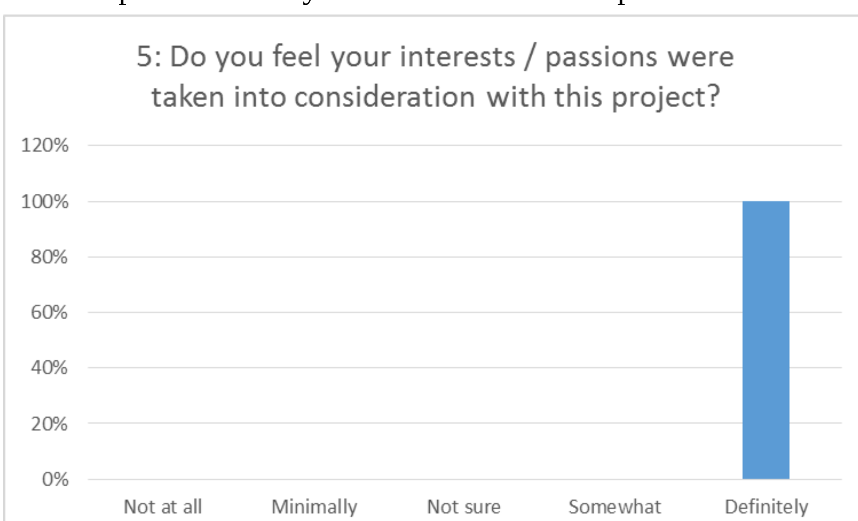


FIGURE 8: STUDENTS FEELINGS OF HOW INTERESTES/PASSIONS WERE CONSIDERED IN THE PROJECT

Question 5 asked about how students felt their interests and passions were taken into consideration for the project. It is excellent to see all students felt as though their individual interests were considered. The most likely explanation for this lies in the complexity of the project as so many different topics were covered.

Question 6 asked if students felt a sense of ownership of the project. This question is very important to gauge how hard students are willing to work toward a common goal. The project leadership attempted to engage students' feeling of ownership by assigning topics each student

FIGURE 9: STUDENTS SENSE OF OWNERSHIP REGARDING THE PROJECT

was passionate about and then having that student present their findings to the rest of the group. This method was used every meeting throughout the project. The method was chosen by the group leader based on experience as a branch manager using this hands-on leadership style. The results are excellent and show that all students not only felt involved in the project but personally responsible for the overall success of the group.

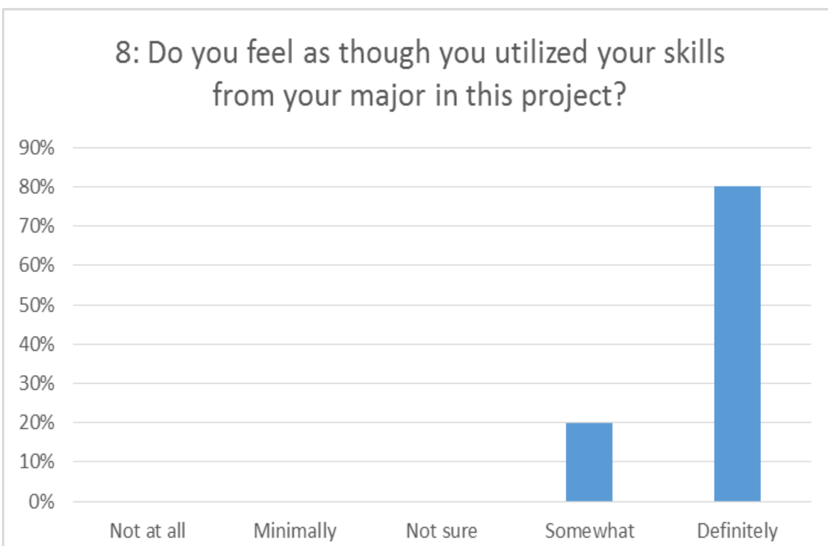


FIGURE 10: STUDENTS SENSE OF HOW THE PROJECT UTILIZED THEIR INDIVIDUAL SKILLS FROM THEIR MAJOR

The final question in this section, question 8, was to find out how students felt their individual skills were utilized by the group in the project. The expectation for this prior to asking the question was that all students would feel the same as all students come from the same background. However, it was clear that not all student members felt the project truly utilized their skills fully as it pertains to mechanical engineering.

The final section of questions was designed to gauge how students perceive the success of the group. Question 9 asked about how challenging the students found the project as the project went on. As can be seen, the perception mostly moves from more challenging to more under control as the semester progresses. The most likely cause of this is the shift of the students involved to each

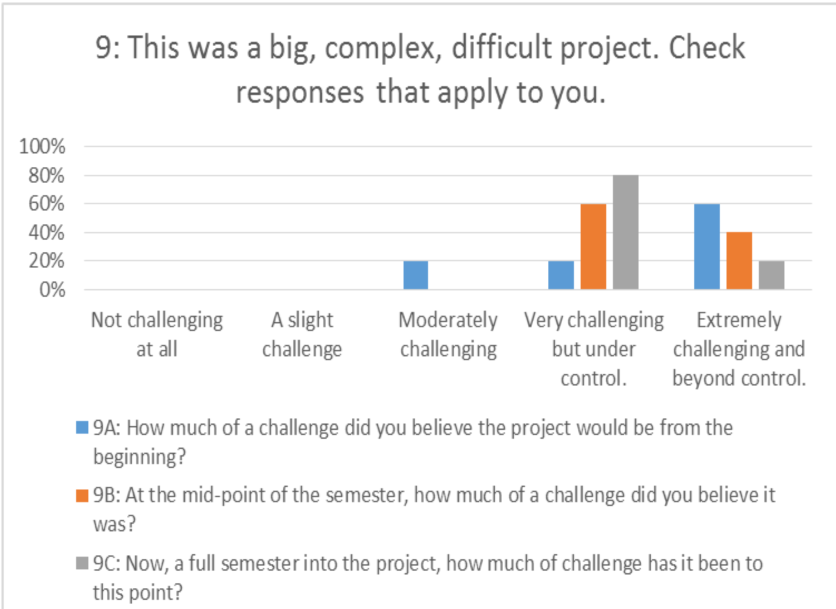


FIGURE 11: STUDENTS' FEELINGS REGARDING THE CHALLENGE OF THE PROJECT

take on more leadership roles. With a group of only five members working on a project of this complexity requires all students to take on leadership position to not only identify the direction

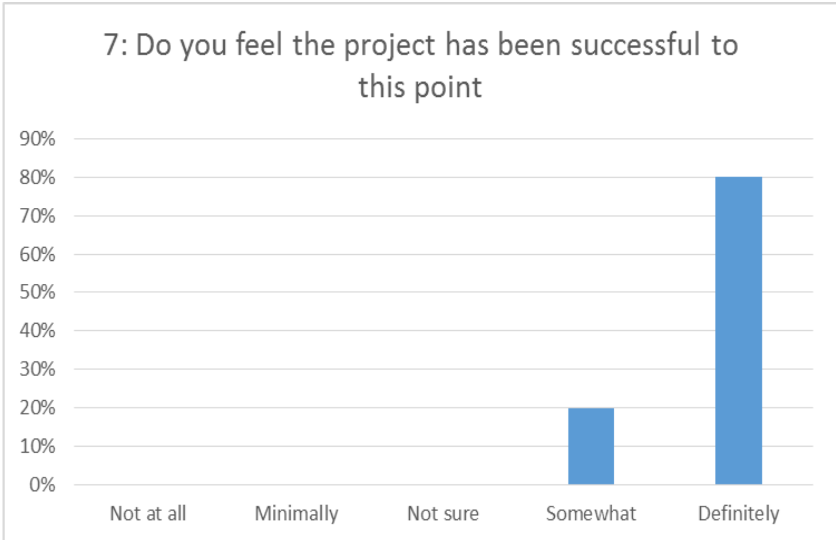


FIGURE 12: PERCEPTION OF THE SUCCESS OF THE PROJECT

of various areas of research but also to become the student-experts in some areas.

Question 7 in this final set was to gather a retrospective view on the overall success of the project. With some of the project still remaining to be completed, this is a very important question to ask this question throughout the semester. The results are very positive and show the students' faith in the success of the project so far. This bodes very well for the portion yet to come.

Overall, the results of the survey show this project has had a very positive effect on students. From perceptions of success to feelings of being included and challenged, the group has become a cohesive unit with a focused goal of success. Each student member involved took on leadership roles to meet the challenge of this daunting project. With this project being the first of its kind, students were unable to seek out assistance on how to tackle such a large undertaking. To this point of the project, it is excellent to see all students have faith in the overall success of the group. It is also promising to see that both primary goals of this paper are confirmed: the success of the group positively correlates with the feelings of ownership and individual students' feelings that their passions are being considered by the group. It is important to note the most important best practice learned from this project, as applies to other group work, would be assigning individual students to a topic and expecting those students to present their findings to the group. This leadership method proved invaluable for student engagement and timely results. Being such a large project, a single group member underperforming could have potentially caused the group to fail. However, each student having a feeling of ownership of the project has provided the team ongoing cohesion and success.

Future Work

At the point of publication for this paper, the group has been selected as semi-finalists for the project competition and await the announcement of finalists. The group has been separated geographically due to work or school assignments and now reside in three time zones. However, with communications technology and planning ahead, the group has remained in contact via weekly remote meetings and has continued to produce effective results for the project. The only remaining steps are a recap of the calculations and preparation of a presentation to be made to NASA. This body of work is also intended to provide a foundation for future student projects.

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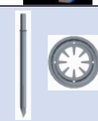
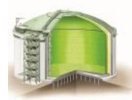
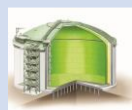
Appendix 1: Bill of Materials

Part #	Part Name	Description	Qty	Units	Picture	Unit Cost	Cost	Sources
1	SUSEE reactor	Nuclear reactor as a heat and power source	2	each		$15,000,000.00	$ 30,000,000.00	No relevant source. Extrapolating from costs of Earth-based reactors. Including cost of fuel
2	Valkyries	NASA's Humanoids	3	each		$ 2,500,000.00	$ 7,500,000.00	Source: http://money.cnn.com/gallery/technology/enterprise/2013/12/19/military-robots/3.html
3	Spiked extractor	Spiked structure that uses a increased surface area to heat up large volumes of lunar regolith	510	each		$ 500.00	$ 255,000.00	No relevant source. Extrapolating from costs of Earth-based reactors
4	Storage Tank (H_2O)	Container for storing water in liquid form in lunar conditions	2	each		$ 50,000.00	$ 100,000.00	http://www.rainharvest.com/rainflo-corrugated-steel-tank-systems.asp + inflation for space based
5	Storage Tank (LH)	Container for storing hydrigen in liquid form in lunar conditions	2	each		$ 720,000.00	$ 1,440,000.00	http://pubs.its.ucdavis.edu/download_pdf.php?id=1130
6	Storage Tank (LOx)	Container for storing oxygen in liquid form in lunar conditions	2	each		$ 500,000.00	$ 1,000,000.00	Extrapolation from: http://pubs.its.ucdavis.edu/download_pdf.php?id=1130
7	RHU (Radioisotope Heater Unit)	RHU's are small devices that use the decay of Pu-238 to provide heat	100	each		$ 4,000.00	$ 400,000.00	http://www.chemicool.com/elements/plutonium.html
8	Electrolysis Plant	Separates liquid water into liquid hygrogen and liquid oxygen through the process of electrolysis	2	each		$ 54,000.00	$ 108,000.00	http://www.hydrogen.energy.gov/pdfs/46676.pdf
9	Electrical connections	Wires to supply power to electrolysis plant	2	each		$ 1,000.00	$ 2,000.00	Extrapolation from: http://www.zoro.com/carol-portabl-cord-163-awg-250-ft-0390-od-
10	Computer connections	Connections to communicate with computer to facilitate autonomous functionality of plant	2	each		$ 5,000.00	$ 10,000.00	Extrapolation from: http://www.zoro.com/carol-portabl-cord-163-awg-250-ft-0390-od-
11	Umbilicus	Wiring connections for water/coolant/and electrical from Lunar surface into crater	2	each		$ 10,000.00	$ 20,000.00	from: http://www.zoro.com/carol-portabl-cord-163-awg-250-ft-0390-od-0276535t01/i/G0917813/?gclid=CjwKEAiAp
12	Oxygen Extraction Apparatus	This device will help extract initial oxygen which will help the spikes penetrate the regolith easily	1	each		$1,250,000	$ 1,250,000.00	
13	Rover	A vehicle designed to move across the surface of the moon	1	each		$38,000,000	$ 38,000,000.00	http://www.armaghplanet.com/blog/nasas-lunar-rover-everything-you-need-to-
14	Compressor (oxygen and hydrogen)	Devices compresses gas from electrolysis processto liquid form	2	each		$ 50,000.00	$ 100,000.00	http://www.diytrade.com/china/pd/11890106/High_Quality_Oxygen_Compressor.html
	Total		**633**				**$ 80,185,000.00**	